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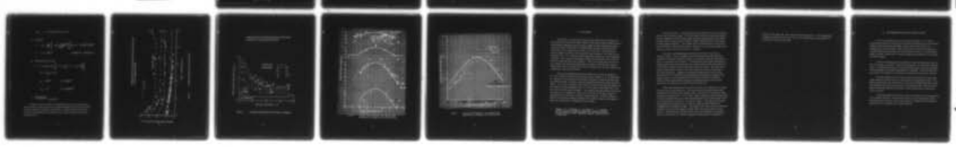

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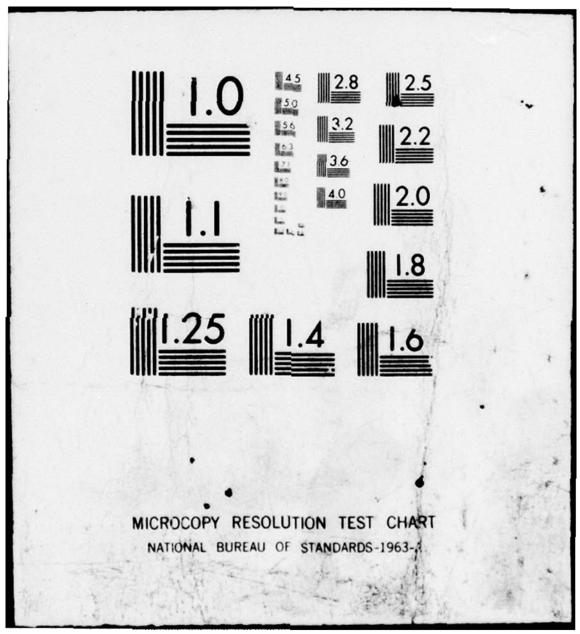
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AERODYNAMIC HEATING ON A MULTI-HUNDRED WATT HEAT SOURCE BASED ON WIND TUNNEL TESTS.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The General Electric Space Division conducted aerodynamic heating tests of the multi-hundred watt heat source configuration of the NASA Mariner-Jupiter/Saturn spacecraft. Curve fit approximations of the data were obtained so that aerodynamic heating studies with any angle of attack history can be performed in a simple manner. Characteristics of theoretical and semi-empirical results for the type of configuration were utilized in obtaining the approximations due to some discrepancies in the data.

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CONTENTS

ILLUSTRATIONS

I. INTRODUCTION

The use of radioactive material in the MHW (Multi-Hundred Watt) heat source requires an evaluation of the risks which may be encountered due to potential malfunctions of the spacecraft mission. Such malfunctions can involve spacecraft breakups which can result in the MHW heat source being exposed to the aerodynamic environment as an independent reentry body. Therefore, estimations of the aerodynamic heating characteristics are presented herein based on wind tunnel tests. These estimates are intended for use in linking a six-degree-of-freedom reentry trajectory computer program with a three-dimensional conduction program so that the thermodynamic performance can be ascertained.

The aerodynamic heating expressions are provided herein for all attitudes of the configuration with the quasi-steady assumption that the dynamic attitude effects are negligible. The expressions were made as simple as possible using linear, parabolic, and trigonometric variations to curve fit the wind tunnel data results given in References 1, 2. This leads to some inaccuracies, but the results should be sufficiently accurate for the intended thermodynamic studies with continuous attitude variations between data points. It is to be noted that the flat ended cylinder with the velocity vector normal to the flat end and the stagnation line of the cylinder wall with the velocity vector normal to the cylinder axis exhibit the same heating characteristics as that of a flat disc as expected. The heating rates, h, presented herein are heating rates normalized by that at the stagnation point of a one foot radius sphere. The conditions are considered to be those for laminar continuum flow.

1 Knight, D., "Aerodynamic Heating on the MHW Heat Source Test Results, "General Electric Space Division, Program Information Release 4432, 2 April 1973.

2 Knight, D., "MHW Aerodynamic Heating Test Final Report," General Electric Space Division, Program Information Release 4665, 5 October 1973.

II. CONFIGURATION

The configuration of the MHW heat source is shown in Figure 1 along with the pertinent nomenclature. It is a flat ended cylinder of radius R and length L with the end having a raised rim encircling the flat recessed face. The 0.813 R radius flat face within the rim is recessed 0.176 R. No attempt is made herein to analyze how flat end characteristics are modified by the rim. The angle of attack, α, is measured by the angle between the axis of the cylinder and the velocity vector. Thus, a zero degree angle of attack is with the velocity vector normal to the end and a 90 deg. angle of attack is with the velocity vector normal to the cylinder axis. A geometric location on the surface is described by a distance x measured along the cylinder from the windward end and an angle θ measured from the stagnation line in a plane perpendicular to the cylinder axis with its vertex at the axis. The range of angles of attack which need to be considered is 0 to 90 deg. and that of the geometric location is 0 to 180 deg. due to symmetry of the configuration.

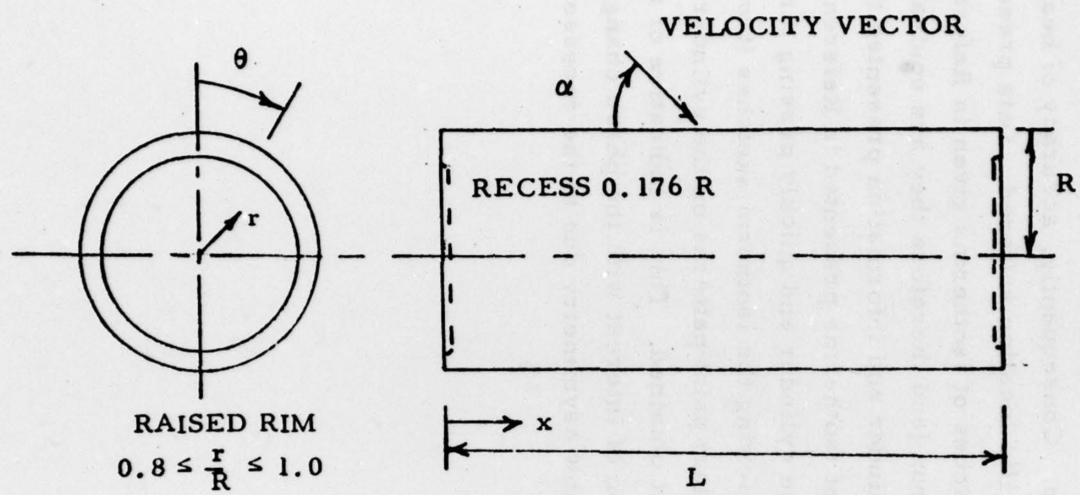

Figure 1 RTG Shell Configuration Test
Model 1/3 Scale
L - 5.543 in. R/L = 0.2154

III. GROUND TEST

The ground test data of References 1, 2 were performed at the NASA Langley Research Center Mach 8 Variable Density Wind Tunnel using the paint phase change technique. Consequently, accuracy of heating rates and details of behavior at a specific location suffered. Data presentations of Reference 2 are based on sketches of isotherms given in Reference 1 for times after the start of the run (and therefore they are equivalent to iso-heating rate lines). The cylinder end information presented the most difficulty since the number of isotherms presented in Reference 1 were sparce due to the paint on the cylinder end quickly passing through the phase change temperature. In reviewing the isotherm sketches it was found that the symmetrical (i.e. circular) paint patterns on the cylinder end for zero deg. angle of attack were not obtained. This is indicative of an accuracy problem for the configuration of interest with the phase change technique and/or possible unpredictable flow asymmetry due to the recessed configuration.

IV. HEATING RATE EXPRESSIONS

The normalized heating rates which were obtained by curve fit approximations of the Reference 2 ground test data are as follows:

a) Cylinder Wall Stagnation Line

$\underline{0 \leq x/L \leq 0.2}$

$$h_{sl} = h_{.5} + 0.042\, k_1 + (0.6\, h_{.5} + 0.2 - 0.042\, k_1)(1 - 5\, x/L)^2$$

$$h_{.5} = 2.81 \sin k_2$$

$$k_1 = 6.0;\; k_2 = 0.415\, \alpha + 5^{\circ} \qquad \text{for } 0 \geq \alpha \leq 15^{\circ}$$

$$k_1 = 11 - \alpha/3^{\circ};\; k_2 = 1.05\, \alpha - 4.5^{\circ} \qquad \text{for } 15^{\circ} \leq \alpha \leq 30^{\circ}$$

$$k_1 = 3.0 - \alpha/15^{\circ};\; k_2 = 1.05\, \alpha - 4.5^{\circ} \qquad \text{for } 30^{\circ} \leq \alpha \leq 45^{\circ}$$

$$k_1 = 0;\; k_2 = 1.05\, \alpha - 4.5^{\circ} \qquad \text{for } 45^{\circ} \leq \alpha \leq 90^{\circ}$$

$\underline{0.2 \leq x/L \leq 0.5}$

$$h_{sl} = h_{.5} + 0.14\,(0.5 - x/L)\, k_1$$

$\underline{0.5 \leq x/L \leq 0.8}$

$$h_{sl} = h_{.5}$$

$\underline{0.8 \le x/L \le 1.0}$

$$h_{sl} = h_{.5} + (0.6\,h_{.5} + 0.2)\,k_3\,(4\text{-}5\,x/L)^2$$

$$k_3 = 0, \qquad \text{for } 0 \le \alpha \le 45^\circ$$

$$k_3 = \alpha/45^\circ - 1.0 \qquad \text{for } 45^\circ \le \alpha \le 90^\circ$$

b) Cylinder Wall (Away from Stagnation Line)

$\underline{0 \le \theta \le \alpha + 30^\circ \le 90^\circ}$

$$h/h_{sl} = 0.824\,\cos^{1.64}(k_4\theta) + 0.176$$

$$k_4 = \alpha/30^\circ \qquad \text{for } 0 \le \alpha \le 30^\circ$$

$$k_4 = 1.0 \qquad \text{for } 30^\circ \le \alpha \le 60^\circ$$

$\underline{30 \le \alpha + 30^\circ \le \theta \le 90^\circ}$

$$h/h_{sl} = 0.824\,\cos^{1.64} k_4\,(\alpha + 30)^\circ + 0.176 \text{ for } 0 \le \alpha \le 60^\circ$$

$$h/h_{sl} = .176 \qquad \text{for } 60^\circ \le \alpha \le 90^\circ$$

$\underline{90^\circ \le \alpha \le 180^\circ}$

$$h/h_{sl} = \left[0.824\,\cos^{1.64} k_4(\alpha + 30^\circ) + 0.176\right] \times$$

$$\left\{1 + \sin\theta - \sin\left[\theta - k_4\,(\theta - 90^\circ)\right]\right\} \text{for } \theta \le \alpha \le 60^\circ$$

$$h/h_{sl} = .176 \sin\theta \text{ for } 60^\circ \leq \alpha \leq 90^\circ$$

c) End Rim

$$h = 3.5 - \frac{\alpha}{30^\circ}\left[1 - \left(\frac{1 - \theta/180^\circ}{\alpha/80^\circ}\right)^2\right] \quad \text{for } 0 \leq 1 - \theta/180^\circ \leq \alpha/80^\circ$$

$$h = 3.5 - \alpha/30^\circ \quad \text{for } \alpha/80^\circ \leq 1 - \theta/180^\circ \leq 1.0$$

d) Recessed Face at End

$$h = 1.4 \sin(90 - \alpha)\left[1 + 2.34\left(\frac{r}{R}\right)^2 \left(1 - k_5 \sin\frac{\theta}{2}\right)\right]$$

$$\text{for } 0 \leq \frac{r}{R} \leq 0.813$$

$$k_5 = \alpha/15^\circ \quad \text{for } 0 \leq \alpha \leq 15^\circ$$

$$k_5 = 1.0 \quad \text{for } 15^\circ \leq \alpha \leq 90^\circ$$

e) Leeward End

$h = 0$ (assumed)

Figures 2 and 3 present the comparisons of the curve fit approximations and the data points for the cylinder stagnation line and the cylinder end in the plane of symmetry respectively. Figure 4 and 5 present the cylinder off-stagnation line comparisons for various distances from the windward end.

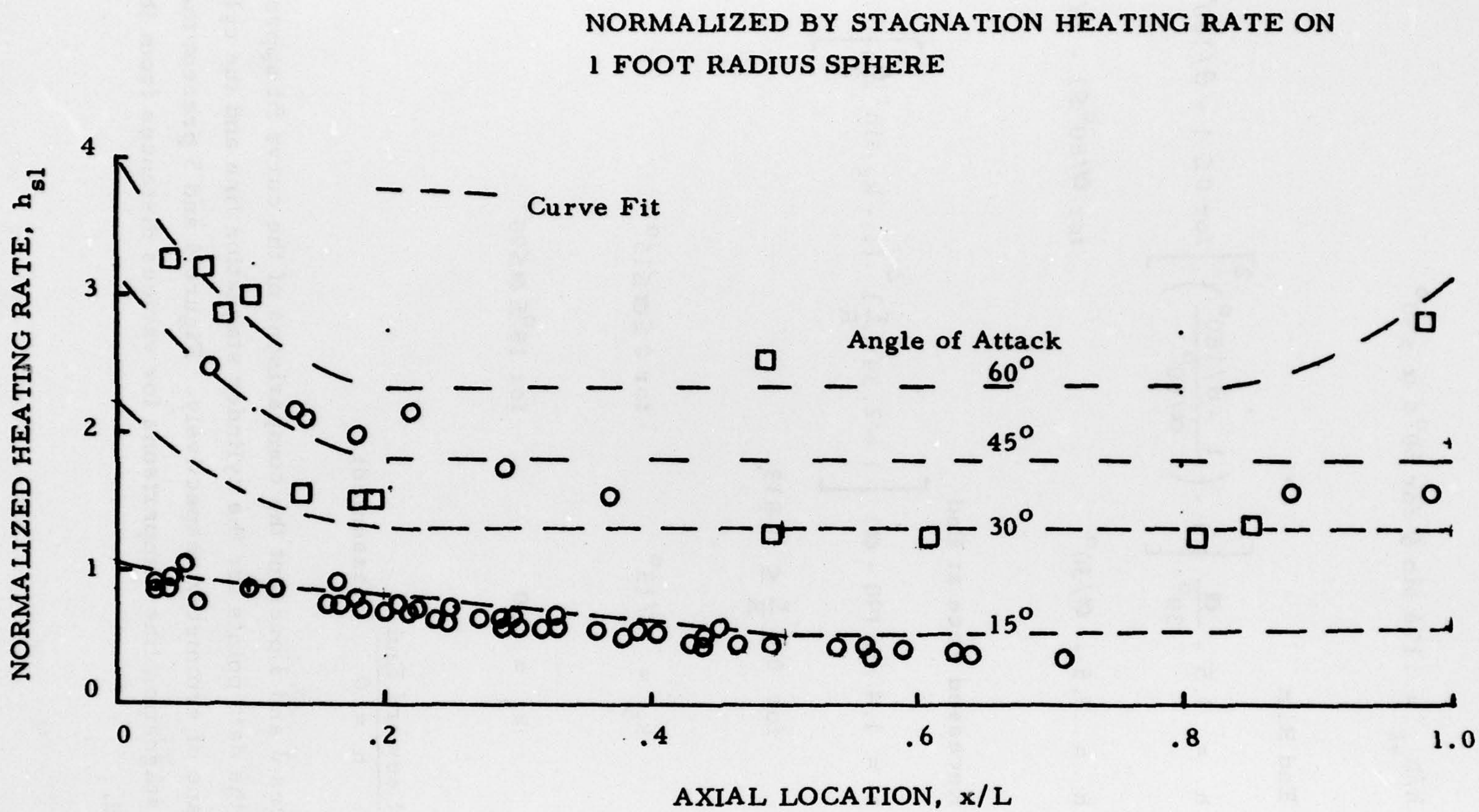

Figure 2. Cylinder Stagnation Line Heating Rate

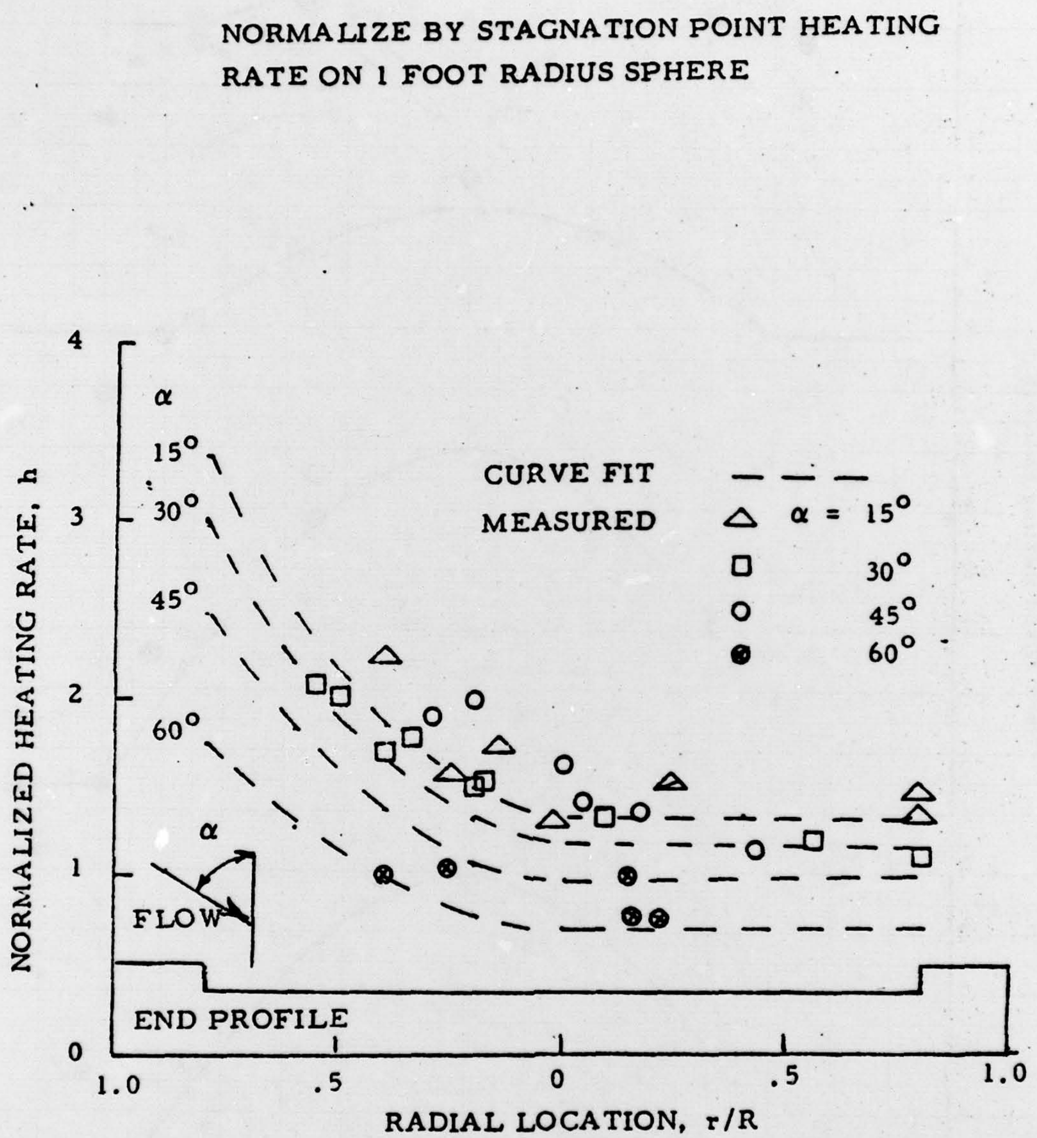

Figure 3. Cylinder End Heating Rate In Plane of Symmetry

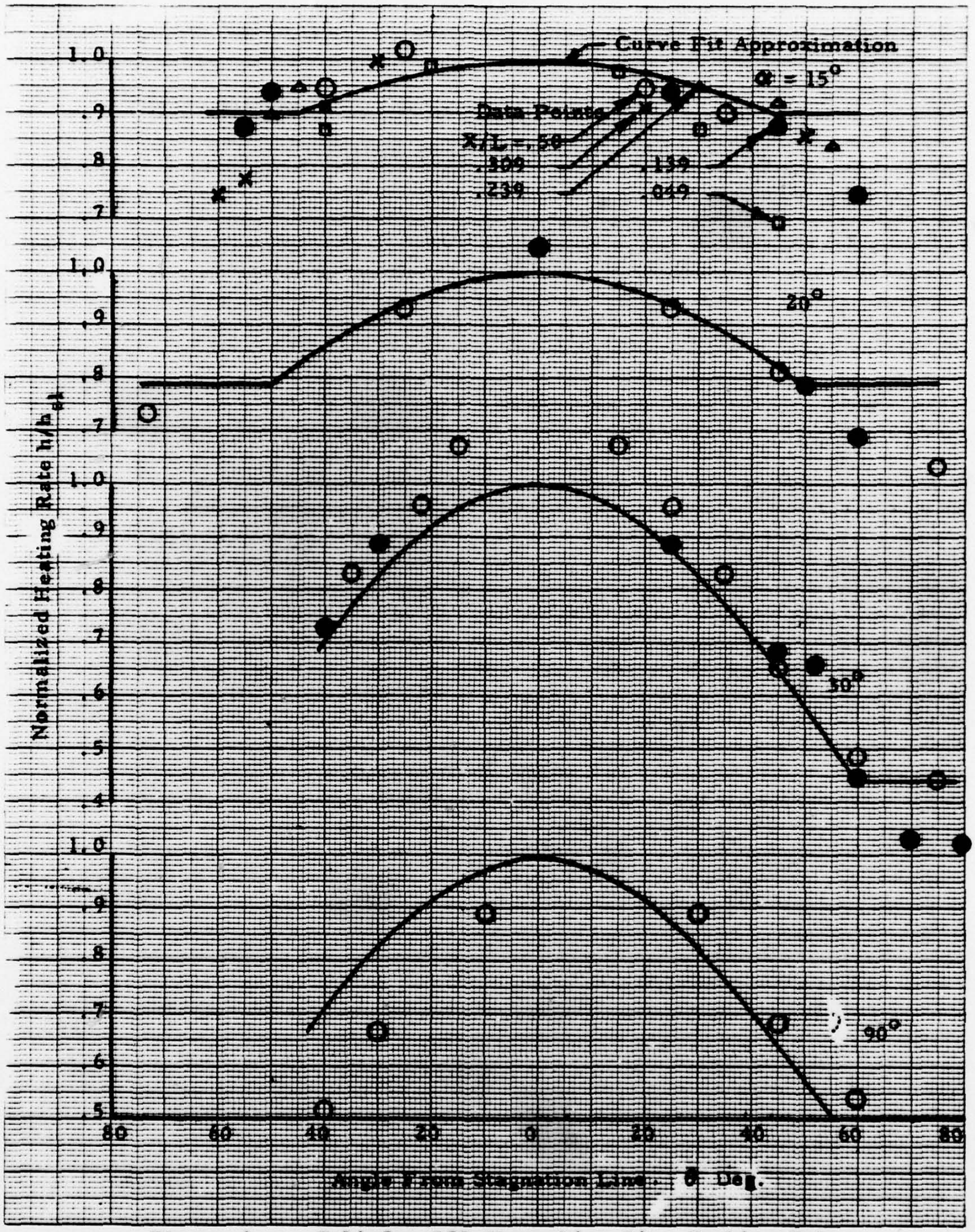

Figure 4 Cylinder Off-Stagnation Line Heating Rate Normalized by Stagnation Line Heating Rate

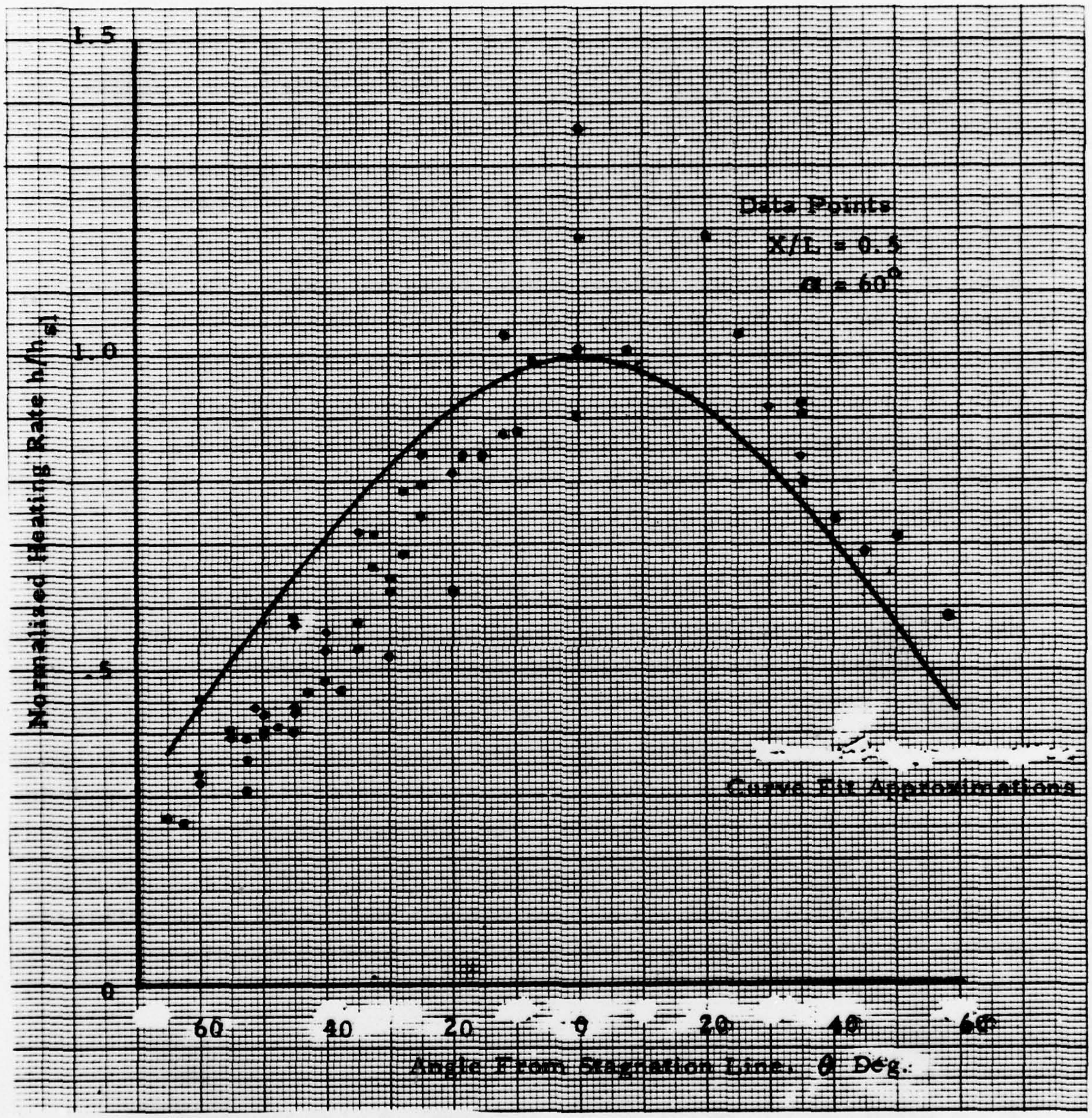

Figure 5 Cylinder Off-Stagnation Line Heating Rate Normalized by Stagnation Line Heating Rate

V. DISCUSSION

In general, the heating distribution data of Reference 2 behaved as described by the equations above. However, the near constant heating level at the cylinder stagnation line for 90 deg. angle of attack indicated hot spots during the tests. Reference 2 interpreted the hot spots as being facility characteristics so they were ignored in the curve fits. Decreasing the angle of attack to 60 deg. did not exhibit these hot spots. The level of the heating at $x/L = 0.5$ is based on that measured in the tests at the high angle of attack. The variation with angle of attack was assumed to be similar to that for swept infinitely long cylinders. The curve fitting near the ends of the cylinder was primarily influenced by the data for the 60 deg. angle of attack data, since discrepancies at the low heating rates for low angles were considered to be of less concern.

The measured heating rate distributions away from the stagnation line were similar to those for the swept infinite cylinder (e.g. see Reference 3). However, the measured distributions indicated a trend of constant rate from about 60 deg. to 90 deg. from the stagnation line at the lower angles of attack. It is seen in Figures 4 and 5 that in several cases the data points are off center from the stagnation line (i.e., $\theta = 0$) which is possibly due to the inaccuracies of the paint technique. The cylinder leeside heating distribution was taken to be trignometric with a zero minimum at 180 deg. from the stagnation line for 30 deg. or greater angle of attack. At lower angles of attack, the minimum heating is allowed to increase so that at zero angle of attack the distribution is independent of the angle.

3 Thomas, A. C., Perlbachs, A., and Nagel, A. L., "Advanced Reentry System Heat Transfer Manual for Hypersonic Flight," Air Force Flight Dynamic Laboratory Report, AFFDL-TR-65-195, October 1966.

The References 1, 2 data results for the heating rates on the cylinder surface were relatively good. The distribution behaved as would be expected with the stagnation line at 90 deg. angle of attack indicating flat disc characteristics with a change toward slender cylinder characteristics as the angle of attack approached zero. The change-over of characteristics occurred in the 45 to 60 deg. angle of attack range. However, the recessed cylinder end heating results were not as uniform in variation.

The end rim heating data presented by Reference 2 was not in sufficient detail. This is probably due to the fact that the data reduction process for the paint technique involves a one-dimensional heating analysis which is inaccurate near corners. No attempt has been made to provide for heating data at the corners between the cylinder and the end rim surface nor on the inner cylinder surface which forms the end recess. The user of the equations presented is free to fair them around the corners according to his own convenience. Maximum normalized heating on the end rim was indicated to be 3.5 with the area experiencing this heating decreasing with angle of attack. The distribution was arbitrarily fitted by a quadratic function of the angle from the leading or stagnation point on the rim and assumed to be constant in a radial direction on the rim.

The measurements for the recessed end of the cylinder at zero angle of attack were not symmetrical. The most symmetrical distribution was obtained on one of the 5 deg. angle of attack runs with the rim heating being somewhat unsymmetrical. At a 15 deg. angle of attack the heating rate along the leeward radius of the recessed end decreased to that at the center of the end in the plane of symmetry. As seen in Figure 3, the plane of symmetry heating data distributions for 45 to 60 deg. angle of attack indicate an unexplained non-monatonic shape. The shape of the curve fits were assumed parabolic as for the low angles of attack where the heating rates are the highest. The distribution along a radius away from the plane of symmetry was at a lower level, the relative magnitude being fitted to a trigometric

function of the angle, θ, away from the symmetry plane. A term applicable to angles of attack of less than 15 deg. was included so that a symmetrical distribution results at zero deg.

VI. RECOMMENDATION FOR GROUND TESTS

In view of the difficulties with the paint technique, it is recommended that model tests using more accurate methods such as a thin walled model instrumented with heat gages, particularly at the ends of the configuration, be performed. Due to the several corners at the ends and the high heating rates indicated by the Reference 1 tests, it is desirable to obtain accurate results and to verify the heating rate behavior as the angle of attack changes.

Pressure measuring instrumentation is also recommended since the flow at the ends is complex. Pressure information, as well as the heating rates, is required as an input to the three-dimensional conduction program which provides the ultimate thermodynamic response. Pressure data may also provide an insight to the heating rate behavior since they are related.

The test facilities in the subsonic and at least near free-molecular range should be used as well as in the supersonic-hypersonic range. The drag characteristics are believed to be such that the MHW body will quickly lose speed during a free reentry and a relatively long time interval can be spent outside the supersonic-hypersonic speed range before final destruction or impact.

A desirable addition would be to test a simulation of the configuration in the ablated condition. Of particular interest is the end heating characteristics where the sharp corners have become rounded with the resulting alleviation of the regions of the highest heating.